Patent Application of

Wil McCarthy and Gary E. Snyder

for

PROGRAMMABLE DOPANT FIBER

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is entitled to the benefit of Provisional Patent Application Ser.#60/312264, filed 14 August 2001.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention is not the result of federally sponsored research or development.

INCORPORATION-BY-REFERENCE OF MATERIAL SUBMITTED ON A COMPACT DISC

No material has been submitted on compact disc in connection with this invention.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to a device for producing quantum effects: a fiber which is capable of carrying energy and whose exterior surface has quantum dots attached to it which are controlled by said energy. The invention has particular but not exclusive application in materials science, as a programmable dopant which can be placed inside bulk materials and controlled by external signals.

2. Description of the Related Art

The fabrication of very small structures to exploit the quantum mechanical behavior of charge carriers (e.g., electrons or electron "holes") is well established. Quantum confinement of a carrier can be accomplished by a structure whose linear dimension is less than the quantum mechanical wavelength of the carrier. Confinement in a single dimension produces a "quantum well," and confinement in two dimensions produces a "quantum wire."

A quantum dot (QD) is a structure capable of confining carriers in all three dimensions. Quantum dots can be formed as particles, with a dimension in all three directions of less than the de Broglie wavelength of a charge carrier. Such particles may be composed of semiconductor materials (including Si, GaAs, AlGaAs, InGaAs, InAlAs, InAs, and other materials), or of metals, and may or may not possess an insulative coating. Such particles are referred to in this document as "quantum dot particles." A quantum dot can also be formed inside a semiconductor substrate, through electrostatic confinement of the charge carriers. This is accomplished through the use of microelectronic devices of various design (e.g., a nearly enclosed gate electrode formed on top of a quantum well). Here, the term "micro" means "very small" and usually expresses a dimension less than the order of microns (thousandths of a millimeter). The term "quantum dot device" refers to any apparatus capable of generating a quantum dot in

this manner. The generic term "quantum dot," abbreviated QD in certain drawings, refers to any quantum dot particle or quantum dot device.

The electrical, optical, thermal, magnetic, mechanical, and chemical properties of a material depend on the structure and excitation level of the electron clouds surrounding its atoms and molecules. Doping is the process of embedding precise quantities of carefully selected impurities in a material in order to alter the electronic structure of the surrounding atoms (for example, by donating or borrowing electrons from them), and therefore altering the material's electrical, optical, thermal, magnetic, mechanical, or chemical properties. Doping levels as low as one dopant atom per million atoms of substrate can produce measurable changes in the expected behavior of the pure material (for example, by altering the band gap of a semiconductor).

Quantum dots can have a greatly modified electronic structure from the corresponding bulk material, and therefore different properties. Quantum dots can also serve as dopants inside other materials, as described for example in LoCasclo et. al. (2002). Because of their unique properties, quantum dots are used in a variety of electronic, optical, and electro-optical devices.

Kastner (1993) points out that the quantum dot can be thought of as an "artificial atom," since the carriers confined in it behave similarly in many ways to electrons confined by an atomic nucleus. The term "artificial atom" is now in common use (for example, in U.S. Patent 6498,354 to Jefferson et. al, 2002), and is often used interchangeably with "quantum dot." However, for the purposes of this document, "artificial atom" refers specifically to the pattern of confined carriers (e.g., an electron gas), and not to the particle or device in which the carriers are confined.

The term " programmable dopant fiber" refers to a wire or fiber with quantum dots attached to, embedded in, or forming its outer surface. This should not be confused with a quantum wire, which is a structure for carrier confinement in two dimensions only.

Quantum dots are currently used as near-monochromatic fluorescent light sources, laser light sources, light detectors (including infra-red detectors), and highly miniaturized transistors, including single-electron transistors. They can also serve as a useful laboratory for exploring the quantum mechanical behavior of confined carriers. Many researchers are exploring the use of quantum dots in artificial materials, and as programmable dopants to affect the optical and electrical properties of semiconductor materials.

Kastner (1993) describes the future potential for "artificial molecules" and "artificial solids" composed of quantum dot particles. Specifics on the design and functioning of these molecules and solids are not provided. Leatherdale et. al. (2000) describe, in detail, the fabrication of "two- and three-dimensional... artificial solids with potentially tunable optical and electrical properties." These solids are composed of colloidal semiconductor nanocrystals deposited on a semiconductor substrate. The result is an ordered, glassy film composed of quantum dot particles, which can be optically stimulated by external light sources, or electrically stimulated by attached electrodes, to alter its optical and electrical properties. However, these films are extremely fragile, and are "three dimensional" only in the sense that they have been made up to several microns thick. In addition, the only parameter which can be adjusted electrically is the average number of electrons in the quantum dots. Slight variations in the size and composition of the quantum dot particles mean that the number of electrons will vary slightly between dots. However, on average the quantum dot particles will all behave similarly.

The embedding of metal and semiconductor nanoparticles inside bulk materials (e.g., the lead particles in leaded crystal) is also well established. These nanoparticles are quantum dots whose characteristics are determined by their size and composition, and they serve as dopants for the material in which they are embedded, to alter selected optical or electrical properties. However, there is no means or pathway by which these quantum dot particles can be stimulated electrically. Thus, the doping characteristics of the quantum dots are fixed at the time of manufacture and cannot be adjusted thereafter.

In general, the prior art almost completely overlooks the broader materials-science implications of quantum dots. The ability to place programmable dopants in a variety of materials implies a useful control over the bulk properties of these materials. This control could take place not only at the time of the material's fabrication, but also in real time, i.e., at the time of use, in response to changing needs and conditions. However, there is virtually no prior art discussing the use, placement, or control of programmable quantum dots in the interior of bulk materials. Similarly, there is no prior art discussing the placement of quantum dots on the surface of an electrically or optically conductive fiber. There are hints of these concepts in a handful of references, discussed below:

U.S. patent 5,881,200 to Burt (1999) discloses an optical fiber (1) containing a central opening (2) filled with a colloidal solution (3) of quantum dots (4) in a support medium. The purpose of the quantum dots is to produce light when optically stimulated, for example to produce optical amplification or laser radiation. The quantum dots take the place of erbium atoms, which can produce optical amplifiers when used as dopants in an optical fiber. This fiber could be embedded inside bulk materials, but could not alter the materials' properties since the quantum-dot dopants are enclosed inside the fiber. In addition, no means is described for exciting the quantum dots electrically. Thus the characteristics of the quantum dots are not programmable, except in the sense that their size and composition can be selected at the time of manufacture.

U.S. patent 5,889,288 to Futatsugi (1999) discloses a semiconductor quantum dot device which uses electrostatic repulsion to confine electrons. This device consists of electrodes (16a, 16b, and 17) controlled by a field effect transistor, both formed on the surface of a quantum well on a semi-insulating substrate (11). This arrangement permits the exact number of electrons trapped in the quantum dot (QD) to be controlled, simply by varying the voltage on the gate electrode (G). This is useful, in that it allows the "artificial atom" contained in the quantum dot to take on characteristics similar to any natural atom on the periodic table, and also transuranic and asymmetric atoms which cannot easily be created by other means. Unfortunately, the two-dimensional nature of

the electrodes means that the artificial atom can exist only at or near the surface of the wafer, and cannot serve as a dopant to affect the wafer's interior properties.

Kouwenhoven et. al. (1998) describe the process of manupilating an artificial atom confined in a similar device, including changing its atomic number by varying the voltage on a gate electrode. The described device is capable of holding up to 100 electrons, whose "periodic table" is also described, and is different from the periodic table for normal atoms since the quantum confinement region is nonspherical. The materials science implications of this are not discussed. However, Turton (1995) describes the possibility of placing such quantum dot devices in two-dimensional arrays on a semiconductor microchip, explicitly as a method for producing new materials through programmable doping of the substrate. This practice has since become routine, although the spacing of the quantum dot devices is typically large enough that the artificial atoms formed on the chip do not interact significantly, nor produce macroscopically significant doping. Such a chip also suffers from the limitation cited in the previous paragraph: its two-dimensional structure prevents its being used as a dopant except near the surface of a material or material layer.

Goldhaber-Gordon et. al (1997) describe what may be the smallest possible single-electron transistor. This consists of a "wire" made of conductive C_6 (benzene) molecules, with a "resonant tunneling device" or RTD inline which consists of a benzene molecule surrounded by CH_2 molecules which serve as insulators. The device is described (incorrectly, we believe) as a quantum well rather than a quantum dot, and is intended as a switching device (transistor) rather than a confinement mechanism for charge carriers. However, in principle the device should be capable of containing a small number of excess electrons and thus forming a primitive sort of artificial atom. Thus, the authors remark on page 19 that the device may be "much more like a quantum dot than a solid state RTD." The materials science implications of this are not discussed.

U.S. Patent 6,512,242 to Fan et. al. (1999) discloses a fiber-shaped material -- specifically, a quantum wire or a plurality of quantum wires-- which transport electrons

into and out of a quantum dot or plurality of quantum dots. However, this transport is accomplished through "resonant tunneling" rather than through any direct connection between the fiber and the dot. In fact, Fan's diagrams show a definite spatial separation between the dots and the fibers. Furthermore, the quantum dots serve not as artificial atoms but as "resonant coupling elements" which transport electrons between electronic waveguides, or between different ports on the same waveguide. In other words, the dot serves only as a kind of conduit, and there is no means for controlling the number of electrons trapped inside it at any given time, nor for controlling the size or shape of any artificial atom which might briefly (and incidentally) exist there. Thus, Fan's quantum dots could not be used as programmable dopants, and his device could not be used to systematically (i.e., programmably) alter the properties of materials in real time.

U.S. Patent Application Publication US 2002/0079485 A1 to Stinz. et. al (June 27,2002) discloses a "quantum dash" device which can be thought of as an asymmetric quantum dot particle with elongated axes, or as a short, disconnected segment of quantum wire. A plurality of these devices are embedded at particular locations inside a solid material to alter its properties, specifically to enhance the excitation of laser energy within the material. Arguably the quantum dash devices serve as dopants, although the authors do not refer to them as such, and also make no reference to "artificial atoms," nor to the number or pattern of charge carriers confined within the dash.

In a very crude sense these dashes are "programmable," since the resulting structure is a "tunable laser" whose output frequency can be adjusted over a narrow range. However, this tuning is accomplished through "wavelength selective feedback," using an external optical grating to limit the input light frequencies which can reach the dashes inside the material. In their only reference to atom-like behavior, the authors declare, "an ensemble of uniformly sized quantum dashes that functioned as ideal quantum dots would have an atomic-like density of states and optical gain." Selection of the available quantum states is achieved exclusively at the time of manufacture, "with a variety of length-to-width-to-height ratios, for example, by adjusting the InAs monolayer coverage, growth rate, and temperature."

In other words, although they don't describe it this way, the authors are relying on the exact geometry and composition of the quantum dashes to produce artificial atoms of a particular size, shape, and atomic number. While a beam of carefully selected photons can excite these artificial atoms inside the dashes, it cannot alter their fixed size, shape, or atomic number. Moreover, no conduits are provided for this light energy. As a result, the energy affects all the quantum dashes equally, along with the surrounding material in which they are embedded, and if this material is opaque, then the energy cannot reach the quantum dashes at all. In this sense, quantum dashes are merely a special class of quantum dot particles, and cannot serve as programmable dopants unless additional supporting hardware (not described by Stinz et. al.) is provided.

However, it should be noted that the present invention, as described in this application, could employ quantum dashes in the same manner as quantum dot particles, with little change in its essential function.

McCarthy (1999), in a science fiction story, includes a fanciful description of "wellstone," a form of "programmable matter" made from "a diffuse lattice of crystalline silicon, superfine threads much finer than a human hair," which use "a careful balancing of electrical charges" to confine electrons in free space, adjacent to the threads. This is probably physically impossible, as it would appear to violate Coulomb's Law, although we do not wish to be bound by this. Similar text by the same author appears in McCarthy (August 2000) and McCarthy (05 October 2000). Detailed information about the composition, construction, or functioning of these devices is not given.

BRIEF SUMMARY OF THE INVENTION

Accordingly, it is a general object of the present invention to use quantum dots to produce a plurality of real-time programmable dopants wherein the foregoing problems are eliminated.

Another and more specific object of the present invention is to provide an energy-transporting fiber to control the properties of said dopants using external energy sources, even when said dopants are embedded in solid materials, including opaque or electrically insulating materials which would ordinarily isolate said quantum dots from external influences.

Another object of the present invention is to provide a programmable dopant fiber, comprising:

a fiber-shaped material;
a plurality of quantum dot particles or quantum dot devices on the surface of the fiber;
one or more control paths, which carry energy to the quantum dots in order to control their confinement of charge carriers.

The structure, composition, manufacture and functioning of quantum dot particles is taught by Lee (2003), incorporated herein by reference. The structure, composition, manufacture and functioning of quantum dot devices is taught by Futatsugi (1999), incorporated herein by reference. It will be understood by a person of ordinary skill in the art that the quantum dot particles or quantum dot devices employed by the present invention may be of different design than those described by Lee and Futatsugi, but that their operating principles are essentially unchanged.

According to the present invention, charge carriers are driven into the quantum dots by the energy in the control paths, and trapped there through quantum confinement, such that they form artificial atoms which serve as dopants for the surrounding materials. The atomic number of each artificial atom is adjusted through precise variations in the

voltage across the quantum dot which confines it. This alters the doping characteristics of the artificial atoms.

In some embodiments of the present invention, the excitation level of the artificial atom is also controlled, either through additional electrical voltages or through optical or electromagnetic stimulation. Additionally, in some embodiments of the invention the energy in the control paths creates electric fields which affect the quantum confinement characteristics of the quantum dots, producing controlled and repeatable distortions in the size and shape of the artificial atoms, further altering their doping characteristics, with a corresponding effect on the surrounding materials

Since the electrical, optical, thermal, magnetic, mechanical, and chemical properties of a material depend on its electronic structure, and since the embedding of dopants can affect this structure, the programmable dopant fiber offers a means of controlling the interior properties of bulk materials in real time.

Accordingly, several objects and advantages of the present invention are:

(a) that it provides a three-dimensional structure for quantum dots which can be considerably more robust than a nanoparticle film. For example, a contiguous GaAs fiber or metal wire is held together by atomic bonds, as opposed to the much weaker Van der Waals forces which hold nanoparticle films together.

(b) that it provides a method for the electrical and/or optical stimulation of quantum dot particles embedded inside bulk materials. The fiber consists of, or includes, one or more wires or optical conduits which are electrically and/or optically isolated from the material in which they are embedded. These pathways branch directly to the quantum dot particles or devices on the surface of the fiber, providing the means to stimulate them.

(c) that is provides a method for embedding and controlling electrostatic quantum dot devices (and potentially other types of quantum dot devices) inside bulk materials, rather than at their surfaces.

(d) that it permits the doping characteristics of quantum dots inside a material to be controlled by external signals, and thus varied by a user at the time of use. Thus, the properties of the bulk material can be tuned in real time, in response to changing needs or circumstances.

(e) that the programmable dopant fiber can be used outside of bulk materials, in applications where quantum dots, quantum wires, and nanoparticle films are presently used. For example, the programmable dopant fiber can serve as a microscopic light source or laser light source which is both long and flexible.

(f) that multiple programmable dopant fibers can be arranged on a surface to produce two-dimensional materials analogous to nanoparticle films, but much stronger.

(g) that multiple programmable dopant fibers can be woven, braided, or otherwise arranged into three-dimensional structures whose properties can be adjusted through external signals, forming a type of "programmable matter" which is a bulk solid with electrical, optical, thermal, magnetic, mechanical, and chemical properties that can be tuned in real time through the adjustment of the energies in the control paths, which affect the properties of artificial atoms used as dopants.

(h) that the resulting programmable materials, unlike nanoparticle films, can contain artificial atoms of numerous and wildly different types, if desired. Thus, the number of potential uses for the programmable dopant fiber materials is vastly greater than for the materials based on nanoparticle films.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

In the drawings, closely related figures have the same number but different alphabetic suffixes, except for figures 1 and 2 from the prior art, which are closely related.

Figs 1 and 2 are from the prior art, U.S. patent 5,881,200 to Burt (1999), and show a hollow optical fiber containing a colloidal solution of quantum dots in a support medium

Figs 3a and 3b are from the prior art, U.S. patent 5,889,288 to Futasugi (1999), and show a semiconductor quantum dot device which uses electrostatic repulsion to confine electrons.

Figs 4a and 4b are from the present invention, in its preferred embodiment. This is a multilayered microscopic fiber which includes a quantum well, surface electrodes which form quantum dot devices, and control wires to carry electrical signals to the electrodes.

Figure 4c shows, in detail, the functioning of an optional memory layer in the same embodiment.

Figs 5a and 5b disclose an additional embodiment of the present invention, in which the quantum dot devices (quantum well and electrodes) on the fiber's surface are replaced with quantum dot particles.

Figs 6a and 6b disclose a variant of this embodiment, in which the fiber comprises a single control wire with quantum dot particles attached to its exterior surface.

Figs 7a and 7b disclose still another alternative embodiment of the present invention, comprising an ordered chain of quantum dot particles alternating with control wire segments.

Reference numerals for the prior art are not included here. The reference numerals for the present invention are as follows:

(30) Surface electrodes

(31) Barrier layers of quantum well

(32) Transport layer of quantum well

(33) Memory layer, comprising microscopic transistors to switch electrodes on and off. This layer is optional, since this switching can be accomplished external to the fiber.

(34) Control wires

(35) Insulator

(36) Control wire branches to fiber surface

(37) Quantum dot particles

(38) Control wire segments

(QD) Quantum dot region

Please note that Figures 1, 2, 3a and 3b are from the prior art. To prevent confusion, the figures for the present invention are numbered 4 and above.

DETAILED DESCRIPTION OF THE INVENTION

FIG 4: Figures 4a (isometric view) and 4b (end view) show a preferred embodiment of the invention, which is a fiber containing control wires (34) in an insulating medium (35), surrounded by a quantum well (31),(32), plus an optional memory layer (33). The preferred composition of the insulator is a semiconductor oxide such as $SiO2$, although a variety of other materials could be used. The preferred composition of the quantum well is a central or transport layer (32) of a semiconductor

such as GaAs, surrounded by barrier or supply layers (31) of a semiconductor with higher conduction energy, such as AlGaAs. Because of the difference in conduction energies, electrons "fall" preferentially into the lower energy of the GaAs transport layer, where they are free to travel horizontally (that is, within the layer) but are confined vertically (perpendicular to the layer) by the higher conduction energy of the barrier layers. However, our invention is not limited to this particular configuration, and includes quantum wells made from other materials and with other designs, as well as quantum wells designed to trap "holes" or other charge carriers.

The transport layer (32) of the quantum well must be smaller in thickness than the de Broglie wavelength of the charge carriers to be confined in it. For an electron at room temperature, this would be approximately 20 nanometers. Thicker quantum wells are possible, although they will only exhibit quantum confinement of the carriers at temperatures colder than room temperature. Thinner quantum wells will operate at room temperature, and at higher temperatures so long as the de Broglie wavelength of the carriers does not exceed the thickness of the transport layer (32).

The surface of the fiber includes conductors which serve as the electrodes (30) of a quantum dot device, which confine charge carriers in the quantum well into a small space or quantum dot (QD) when a reverse-bias voltage is applied, since the negative charge on the electrodes repels electrons, preventing their horizontal escape through the transport layer. The electrodes (30) are powered by control wire branches (36) reaching to the fiber's surface from the control wires (34) in the fiber's center. In the preferred embodiment, the electrodes, control wires and control wire branches are made of gold, although in principle they could be made of other metals, or other materials, such as semiconductors or superconductors.

Once the charge carriers are trapped in a quantum dot (QD), they form an artificial atom which is capable of serving as a dopant. Increasing the voltage on the electrodes (30) by a specific amount forces a specific number of additional carriers into the quantum dot (QD), altering the atomic number of the artificial atom trapped inside.

Conversely, decreasing the voltage by a specific amount allows a specific number of carriers to escape to regions of the transport layer (32) outside the quantum dot (QD). The preferred embodiment of the invention in Fig. 4a shows six electrodes for each quantum dot device, although more or less could be used, and by selecting the voltages on these electrodes it is possible to alter the replusive electric field, thus affecting size and shape of the quantum dot's (QD) confinement region, and therefore altering the size and shape of the artificial atom trapped inside it, either in conjunction with changes to the artificial atom's atomic number or while holding the atomic number constant. Thus, the doping properties of the artificial atom are adjusted in real time through variations in the signal voltage of the control wires (34) at the fiber's center.

Figure 4c shows the optional memory layer (33), comprising microscopic transistors or other switches which are placed inline with the control wire branches (37) and which serve as switches that are capable of turning voltages to the surface electrodes (30) on and off. The ends of the control wire branch (37) serve as the source and drain electrodes of the switch, and an additional control wire branch (37) is extended from a central control wire (34) to serve as the switch's gate electrode. The preferred form of the switch is a field effect transistor, although numerous other types of switches may be used without affecting the function of the invention. This switching or memory layer is optional, since this switching can be accomplished external to the fiber. However, it is included here for clarity. Collectively, the control wire branches (37), quantum well layers (31) and (32), electrodes (30), and optional memory layer (33) constitute a quantum dot device similar to that described by Futatsugi (1999). While this is a preferred embodiment, our invention is not limited to this particular configuration, and includes quantum dot devices made of other materials or of alternative design, including devices protected by an additional insulating layer (not pictured), either continuous or discontinuous, on top of the electrodes (30) at the fiber's surface.

Note that the exact arrangement of the various layers can be slightly different than is depicted here, without altering the essential functioning of the programmable dopant fiber. For example, the cross-section may be any oval or polygon shape, and the

insulated control wires need not be located at the fiber's center, although that seems to be the most convenient place to locate them.

The preferred manner of using the programmable dopant fiber is to place the fiber or a plurality of fibers, as needed, inside a bulk material (e.g., a semiconductor), or to weave or braid them together into a two-or three-dimensional structure. Material layers (31) and (32) form a quantum well, which traps charge carriers in a quantum (wavelike) manner in the central or transport layer (32).

Voltages are then passed through the control wires (30) from an external source. These voltages pass from the control wires to the control wire branches (36), where they are carried to electrodes (30) on the surface of the fiber. Alternatively, the control wire branches may pass through the optional memory layer (33) which consists of inline transistors or other switches, embedded in an insulating medium, which are capable of switching the voltage pathways open or closed. From the memory layer, the control wire branches then lead to the electrodes (30) at the surface of the fiber. Once the voltage reaches the electrodes, it creates an electrostatic repulsion which affects the carriers trapped in the quantum well, herding them into small areas known as quantum dots, where they form artificial atoms.

Adjustment of the voltages on the electrodes can then affect the characteristics of the artificial atoms, including:

(a) size

(b) shape or symmetry

(c) number of charge carriers

(d) energy levels of the carriers

The resulting changes in the artificial atom can dramatically affect its properties as a dopant.

Depending on the number of control wires inside the fiber and the number of quantum dot devices along its surface, the artificial atoms located near the fiber's surface

(in the confinement layer 32) may all be identical, may represent multiple "artificial elements" in regular or irregular sequences, or may all be different. For example, if the signals sent to each quantum dot device (QD) were identical, the artificial atoms on the fiber might all have an atomic number of 2, equivalent to helium (which would otherwise be extremely difficult to introduce as a dopant). Conversely, if two separate sets of control signals were sent, the artificial atoms could be an alternating pattern of helium (atomic number 2) and carbon (atomic number 6).

FIG. 5: Figures 5a (isometric view) and 5b (end view) show an additional embodiment of the invention, in which the fiber comprises multiple control wires (34) surrounded by insulation (35), with control wire branches (36) leading to quantum dot particles (37) on the surface of the fiber. For clarity, an optional memory layer (33) is included in the figure as well. In this embodiment, the control wires are conductors, but they could also be semiconductors, or superconductors, optical fibers, or other types of conduits for carrying energy to stimulate the quantum dot particles (37). The dimensions can cover a broad range of microscopic values while retaining useful optical, electrical, and other properties for the programmable dopant fiber.

Because they are easily self-assembled in chemical solutions, the preferred form of the quantum dot particles (37) is as spherical nanocrystals consisting of a core of semiconductor material, such as CdSe, surrounded by a passivating shell of crystalline organic material. Dimensions of the core should not exceed the de Broglie wavelength of the carriers to be confined within it. While this is a preferred embodiment, our invention is not limited to this particular configuration, and includes quantum dot particles of other shapes or made using other materials and methods. Quantum dot particles may be deposited onto a substrate by evaporation as described by Lee (2003) and Leatherdale et. al (2000), and this is the preferred method for depositing them onto the fiber. Attachment to the fiber is readily accomplished by means of van der Waals forces, although active "molecular tethers" may be added to the shell and/or fiber as described by Lee (2003) in order to bond the quantum dot particle (37) chemically to the insulator (35) or to the control wire branches (36).

The operation of this embodiment is very similar to the previous one, with the exception that the carriers are confined in quantum dot particles (37) rather than by electrostatic repulsion and a quantum well. Voltages (or optical energy) are passed through the control wires (34) from an external source, and brought to the fiber's surface via control wire branches (36). These voltages are then carried to the quantum dot particles (37). Placing the fiber adjacent to a grounded conductive or semiconductive material, including another programmable dopant fiber, produces a ground path from the control wire branches which leads through the quantum dot particles, greating a voltage across the particles and forcing charge carriers into quantum confinement inside them, where they form artificial atoms. Increasing the voltage in the control wires drives additional carriers into the quantum dot particles (37), increasing the atomic number of the artificial atoms inside them. Additionally, electrical or optical energy passed through the control wires can increase the excitation level of the artificial atoms.

This stimulation can thus affect the properties of the artificial atoms contained in the quantum dot particles, including:

(a) number of carriers

(b) energy levels of the carriers

As before, the resulting changes in the artificial atom can dramatically affect its properties as a dopant.

Depending on the number of control wires inside the fiber and the number of quantum dot particles along its surface, the artificial atoms located in the quantum dot particles may all be identical, may represent multiple "artificial elements" in regular or irregular sequences, or may all be different. In the case of the specific embodiment shown in Figure 5a and 5b, there are four control paths, so each quarter-arc of the fiber's surface could receive different control signals and display different doping characteristics. Thus, the fiber could have up to four "stripes" of different dopant running along its length.

FIG. 6: Figures 6a (isometric view) and 6b (end view) show another additional embodiment, in which quantum dot particles (37) are attached to the surface of a non-insulated control wire (34). In general, this wire would be an electrical conductor, but could be another type of conduit for carrying energy to stimulate the quantum dot particles, such as a semiconductor, superconductor, or optical fiber. Dimensions can once again cover a broad range of microscopic values.

Because they are easily self-assembled in chemical solutions, the preferred form of the quantum dot particles (37) is as spherical nanocrystals consisting of a core of semiconductor material, such as CdSe, surrounded by a passivating shell of crystalline organic material. Dimensions of the core should not exceed the de Broglie wavelength of the carriers to be confined within it. While this is a preferred embodiment, our invention is not limited to this particular configuration, and includes quantum dot particles of other shapes or made using other materials and methods. Quantum dot particles may be deposited onto a substrate by evaporation as described by Lee (2003) and leatherdale et. al. (2000), and this is the preferred method for depositing them onto the fiber. Attachment to the fiber is readily accomplished by means of van der Waals forces, although active "molecular tethers" may be added to the shell and/or fiber as described by Lee (2003) in order to bond the quantum dot particle (37) chemically to the control wire (34).

The operation of this embodiment is similar to the previous one, with the exception that the fiber comprises a single control wire (34), with quantum dot particles (37) attached to its outer surface. Once again, the quantum dots are stimulated by voltage (or optical energy) passing through the control wire to a ground path which includes the quantum dot particles,stimulating them as described above. This stimulation can then affect the properties of the artificial atoms contained in the quantum dot particles, including:

(a) number of carriers

(b) energy levels of the carriers

As before, the resulting changes in the artificial atom can dramatically affect its properties as a dopant.

The capabilities of this embodiment are more limited, in that (barring minor variations in the size and composition of the quantum dot particles) all the artificial atoms along the fiber cannot be controlled separately or in subgroups, and will therefore have the same characteristics, and no controlled patterning of different artificial dopant species is possible, except at the time of manufacture.

FIG. 7: Figures 7a (isometric view) and 7b (end view) show still another additional embodiment, in which control wire segments (38) alternate with quantum dot particles (37). The dimensions of both the wire segments and the quantum dot particles, while generally microscopic, could cover a broad range of values while retaining useful properties for the programmable dopant fiber.

The operation of this embodiment is similar to the previous one, with the exception that the quantum dot particles (37) are not attached to the surface of the fiber, but are an integral part of its structure, alternating with control wire segments (38). Because they are easily self-assembled in chemical solutions, the preferred form of the quantum dot particles (37) is as spherical nanocrystals consisting of a core of semiconductor material, such as CdSe, surrounded by a passivating shell of crystalline organic material. Dimensions of the core should not exceed the de Broglie wavelength of the carriers to be confined within it. Control wire segments (38) are metallic, and bonded chemically to "molecular tethers" on the quantum dot particles (37), per Lee (2003). While this is a preferred embodiment, our invention is not limited to this particular configuration, and includes quantum dot particles and control wire segments made and joined using other materials and methods, including the molecular wires and quantum dots described by Goldhaber-Gordon et. al. (1997).

A voltage (or optical energy) is passed through the control wire, and passes directly into and through the quantum dot particles, stimulating them as described above.

This stimulation can then affect the properties of the artificial atoms contained in the quantum dot particles, including:

(a) number of carriers

(b) energy levels of the carriers

As before, the resulting changes in the artificial atom can dramatically affect its properties as a dopant.

The capabilities of this embodiment are even more limited than the previous one, in that resistive losses across each quantum dot particle will cause the voltage to drop significantly across each segment of the fiber. Thus, each successive artificial atom along the fiber's length will have a lower voltage (or illumination) than the one before it. Thus, the artificial atoms cannot be individually controlled and will not be identical. Instead, the user may select a sequence of artificial elements, of successively lower energies, to be presented by the fiber. For example, the fiber might contain a number of artificial atoms bearing atomic number 6, followed by a number bearing atomic number 5, and so on. This is far from the ideal form of a programmable dopant fiber, but it does provide a unique doping capability which the prior art cannot duplicate.

From the description above, our programmable dopant fiber can be seen to provide a number of capabilities which are not possible with the prior art:

(a) The ability to place programmable dopants in the interior of bulk materials and to control the properties of these dopants in real time, through external signals. In contrast, the properties of dopants based solely on quantum dot particles can only be controlled at the time of manufacture.

(b) The ability to form programmable materials containing "artificial atoms" of diverse types. In contrast, programmable materials based on nanoparticle films can contain only multiple instances of one "artificial element" at a time.

Also from the above description, several advantages over the prior art become evident:

(a) Materials based on programmable dopant fibers will, in general, be much stronger than materials based on nanoparticle films.

(b) Programmable dopant fibers can be used in numerous applications where quantum dots and quantum wires are presently employed. However, the programmable dopant fiber provides isolated energy channels for the optical or electrical stimulation of the quantum dots, permitting the dots to be excited without also affecting the surrounding medium or materials. For example, light can be passed through a quantum dot by means of the fiber, without also being shined on or through surrounding areas, except through the fiber itself. Similarly, an electrical voltage can be channeled to a quantum dot without passing through the surrounding medium, except through the fiber. Thus, programmable dopant fibers can be used in numerous applications where ordinary quantum dot devices or particles would not operate, or would disrupt the surrounding material in uncontrolled ways.

Accordingly, a person of ordinary skill in the art will see that the programmable dopant fiber of this invention can be used as a real-time programmable dopant inside bulk materials, as a building block for new materials with unique properties, and as a substitute for quantum dots and quantum wires in various applications (e.g., as a light source or laser light source).

Although the description above contains many specificities, these should not be construed as limiting the scope of the invention but merely providing illustrations of some of the presently preferred embodiments of this invention.

There are various possibilities for making the programmable dopant fiber of different materials, and in different configurations. The most advantageous configurations are the smallest, since smaller quantum dots can contain charge carriers at

higher energies (shorter de Broglie wavelengths) and thus display atom-like behavior at higher temperatures. The smallest conceivable programmable dopant fiber would be similar in design to the single-electron transistor described in Goldhaber-Gordon et. al (1997), although molecules the size of benzene rings or smaller, if employed as quantum dot particles, will be unable to hold large numbers of excess charge carriers. This limits their usefulness in generating artificial atoms. A somewhat larger but more practical design is to employ electrically conductive nanotubes, such as a carbon nanotubes, as the control wire segments (38), and fullerene-type molecules, such as carbon fullerenes, as the quantum dot particles (37).

Numerous other variations exist which do not affect the core principles of the invention's operation. For example, the fiber could have non-circular shapes in cross-section, including a flat ribbon with quantum dots on one or both sides; the "artificial atoms" could be composed of charge carriers other than electrons, the control wires could be replaced with semiconductor, superconductor, optical fiber, or other conduits for carrying energy; the control wires could be antennas for receiving signals and energy from electromagnetic waves; any of the embodiments listed here could be replicated on a molecular scale through the use of specialized molecules such as carbon nanotube wires and fullerene quantum dot particles; the quantum dots could be other sorts of particles or devices than those discussed herein, so long as they accomplish the quantum confinement necessary for the formation of artificial atoms; the number and relative sizes of the quantum dots with respect to the fiber could be significantly different than is shown in the drawings.

Thus the scope of the invention should be determined by the appended claims and their legal equivalents, rather than by the examples given.